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Simplified approach of turbulent film condensation on an inclined elliptical tube

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Abstract

The present theoretical study investigates turbulent film condensation on an inclined elliptical tube. Adopting the assumption of an isothermal wall surface, the energy equation, forced balance equations and thermal balance equations are derived to describe the phenomena of the condensate film. Results are obtained for the heat transfer coefficient over a wide range of vapor velocities, i.e. low condensation parameter to high condensation parameter. The optimal inclination angle of the tube in different length–radius ratios and eccentricity can be obtained in the present results. This study also discusses the influence of the degree of eccentricity of the elliptical tube on the heat transfer coefficient. Finally, a comparison is provided between the results of the present study and those reported in a previous theoretical study. It is found that a good agreement exists between the two sets of results.

Keywords: Inclined; Turbulent; Condensation; Eccentricity

1. Introduction

Nusselt, who is regarded by many as the pioneering investigator of film condensation, conducted an investigation into laminar film condensation on surfaces of various forms in 1916. Since that time, various other researchers have also studied laminar film condensation of quiescent vapors. For example, Sparrow and Gregg [1] considered the problem of vapor condensation on horizontal cylinders. Meanwhile, Dhir and Lienhard [2] proposed a general integral method, based largely on Nusselt's work, to predict the heat transfer coefficient for the non-circular cross-section condensation problem. Their study focused particularly on the effects of non-uniform gravity.

Shekriladze and Gomelauri [3] investigated the problem of laminar film condensation of flowing vapor and analyzed film condensation on horizontal tubes under low velocity vapor flow conditions. The results indicated that the shearing stress on the friction surface depends on the momentum transferred by the suction mass. A review of the literature shows that various researchers have studied forced convection in laminar film condensation on horizontal tubes. For example, Fujii et al. [4] studied the two-phase boundary layer equations of laminar film condensation on a horizontal cylinder. It was shown that the mean heat transfer coefficient for downward vapor flow could be expressed as $Nu = x(1 + \frac{0.276}{x^4 FrS})Re^{0.5}$, where $x = 0.9(1 + \frac{1}{S(\rho_l \mu_l / \rho_v \mu_v)^{0.5}})$. Furthermore, the numerical predictions of the heat transfer coefficients generated using this expression were shown to be in good agreement with the experimental results. In a later study, Rose [5] considered the effect of the pressure gradient on forced convection laminar film condensation on a horizontal tube. Two significant findings were reported, namely (a) the pressure

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Nomenclature

C_p	specific heat of condensate at constant pressure (J/kg K)
d_e	equivalent circular diameter of elliptical tube (Eq. (23))
f	friction coefficient
$\bar{f}$	average friction coefficient
F	condensation parameter, $2/(SFr)$
Fr	Froude number, $u_\infty^2/g(d_e/2)$
Gr	Grashof number, $\frac{g(d_e/2)^3}{v_l^2}\frac{\rho_l-\rho_v}{\rho_l}$
g	acceleration due to gravity (m/s^2)
h_{fg}	latent heat (J/kg)
k	thermal conductivity (W/m K)
L	tube length (m)
L^+	dimensionless tube length, $2L/(d_e \tan\phi)$
Nu_R	local Nusselt number
Nu	local peripherally average Nusselt number
Nu_m	mean Nusselt number for whole tube surface
n	constant (0.805)
P	interfacial shear parameter, $\frac{\rho_v}{\rho_l}(\frac{v_l}{v_v})^{n-1}Gr^{1.4/6}$
Pr	Prandtl number
R	equivalent circular radius of elliptical tube, $d_e/2$
R_x^+	shear radius, $d_e u_x^*/(2v_l)$
R_x^*	wall shear parameter, $R_x^+/Gr_{d_e/2}^{1/3}$
Re	Reynolds number
S	sub-cooling parameter, $C_p(T_s - T_w)/(h_{fg}Pr)$
St	Stanton number, $Nu/(RePr)$
T	temperature (K)
T^+	dimensionless temperature, $(T - T_w)/(T_s - T_w)$
u_∞	vapor velocity of free stream (m/s)
u	condensate velocity (m/s)
u_x^*	shear velocity in x-direction, $\sqrt{\tau_{wx}/\rho}$
u_z^*	shear velocity in z-direction, $\sqrt{\tau_{wz}/\rho}$
u_x^+	dimensionless velocity, u_x/u_x^*
x	peripheral coordinate (m)
y	coordinate measured distance normal to surface (m)
y^+	dimensionless distance, yu_x^*/v_l
Z	axial coordinate (m)
Z^+	dimensional axial coordinate, $2z/(d_e \tan\varphi)$

Greek symbols

δ	condensate film thickness (m)
δ^+	dimensionless film thickness, $\delta u_x^*/v_l$
φ	tube inclination angle with the horizontal
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
$\tau_{\delta x}$	interfacial vapor shear in x-direction
$\tau_{\delta z}$	interfacial vapor shear in z-direction
τ_{wx}	wall shear in x-direction
τ_{wz}	wall shear in z-direction
θ	angle measured from top of tube
ϕ	angle between the tangent to tube surface and the normal to direction of gravity
ε_m	eddy diffusivity for momentum
ε_h	eddy diffusivity for energy

Subscripts

l	liquid
e	edge of vapor boundary layer
s	saturation
v	vapor
w	tube wall
x	x-direction
z	z-direction
δ	vapor–liquid interface

gradient gives rise to an increase in the heat transfer coefficient over the forward part of the tube, particularly at higher values of $\frac{\rho_v h_{fg} v}{\Delta T K}$, and (b) the pressure gradient promotes an instability in the condensation film at certain locations over the rear half of the tube when $\frac{\rho_l g d}{8\rho_v u_\infty^2} < 1$.

Sarma et al. [6] investigated turbulent film condensation on a horizontal tube with isothermal wall conditions under an external flow of pure vapor. The interfacial shear was solved by means of the Colburn analogy. The numerical results were found to be in good agreement with the experimental data.

The studies presented above involved condensation on tubes with circular cross-sections. However, it is reasonable to assume that an elliptical tube whose major axis is aligned with the direction of gravity should also provide some of the advantages described above. For the case of free-convection film condensation on a horizontal tube, Cheng and Tao [7] found that the heat transfer coefficient performance of a horizontal elliptical tube is superior to that of a circular tube with the same condensation surface area. Meanwhile, for free and forced convection film condensation on a horizontal elliptic tube, Yang and Hsu [8] determined that for values of eccentricity in the range $e = 0.8$–8.95, the mean heat transfer was enhanced by approximately 16% at high values of F (low vapor flow velocity) and by 11% at low values of F compared to the case of a circular tube with an equal condensation surface area. Memory et al. [9] applied a Nusselt type analysis to the condition of free convection and revealed that an elliptical tube yielded an improvement of almost 11% in the heat transfer coefficient compared to a circular tube. For the case of forced convection, the interfacial shear was estimated in two ways: firstly, by using an asymptotic value of the shear stress under conditions of an infinite condensation rate, and secondly by